ADHESION AND COLD WELDING

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INTRODUCTION

Studies on the solid state adhesion of metals have been conducted at National Research Corporation for the past several years under the sponsorship of the National Aeronautics and Space Administration and the United States Air Force. Since adhesion has been observed for metals and alloys under widely varying conditions, there is a need to distinguish among the effects of the more important variables controlling the bonding mechanism. This paper deals with a variety of experimental observations on adhesion mechanisms carried out at National Research Corporation.

The general objective has been to obtain additional information as to the conditions under which metals and alloys of engineering importance for space applications will adhere to one another with sufficient tenacity to hinder the relative motion or subsequent separation of components of mechanical and electrical devices used in space exploration. Such devices include bearings, solenoids, valves, slip rings, mating flanges, conical rendezvous mating surfaces, etc.

Even a small amount of adhesion would be disastrous in many cases on a space vehicle since power on such craft is ordinarily very limited and mechanical components must work freely. There is, therefore, an important requirement for quantitative data on adhesion.

In addition, however, to the preventative aspect of adhesion in moving components, the cold welding phenomenon may be considered in a more positive light as a relatively convenient joining technique in space or vacuum. Metal-to-metal bonds formed by the cold welding process exhibit important advantages such as the absence of a heat-affected zone surrounding the weldment, thus avoiding the formation of brittle or weak intermetallic phases. For the same reason, dissimilar metals which cannot be welded by conventional methods due to brittle phase formation or relative insolubility, can be joined by room temperature adhesion techniques.

The adhesion (cold welding) technique tends to have possible future potential in many fields. At present, its application is directed commercially toward the electronics and space industry. In the electronic industry possible applications are the fabrication of metal-to-semi-conductor bonds and the wiring of micro circuitry. The technique may eliminate the formation of brittle intermetallic phases which usually result in high electrical resistance and weak mechanical bonds. On the other hand, the adhesion technique can possibly be utilized in the fabrication of components and subassemblies in such future space programs as Apollo and M.O.L.

To fully understand the work presented, an acquaintance with the terminology of adhesion is helpful. The following definitions will allow a more complete understanding of this report:

Adhesion (cold welding) - The ability of two separate atoms, molecules, or materials to form a common bond.

Adhesion Coefficient ($\propto$) - The ratio of the force required to rupture the cold welded bond and the force required to form the bond.

Compressibility Factor (C) - The ratio of applied stress required to form the cold welded bond and the actual yield stress of the test material. In the case of dissimilar materials, the yield stress of the softest material should be used.

EXPERIMENTAL TECHNIQUES

Since the cold welding process is extremely sensitive to the presence of surface contaminant films, such as metal oxides or organic layers, studies of the adhesion phenomonon have been carried out in ultrahigh vacuum systems in which a major portion of the surface contaminants may be desorbed. The kinetics of oxide formation are directly proportional to the oxygen partial pressure; generally vacuum levels below 10^{-8} torr are required to maintain oxide-free surfaces for a finite time period during testing.

Several surface cleaning techniques have been employed in adhesion investigations at NRC including thermal outgassing, surface cleavage, wire brush abrasion, and ion bombardment. In particular, wire brush abrasion in vacuum has proved to be a simple, useful method for removing impurity films from test surfaces although transfer of brush material to the surfaces as well as surface scoring and roughening was encountered.

To achieve strong adhesion forces over large areas for engineering materials, surface contact stresses must be equivalent to the yield stress of the metal components. Surface plasticity is required to broaden the interfacial area of atomic contact and to relieve elastic stresses concentrated at localized surface asperities. In experimental studies, compressive test assemblies, as shown in Fig. 1, generating up to 2000 lbs. of force, were used to obtain contact stresses up to 50,000 psi. Motor driven loading units with integral load cells were utilized for the tensile forces. In addition to axial load mechanisms, rotary drive components have also been used to impose rotational shear stresses combined with normal stresses.

EXPERIMENTAL APPROACH

The main approach to the experimental study of the adhesion phenomena was to design a testing program to determine the effect of several critical parameters on the ability to form a cold welded bond. Adhesion tests were conducted on similar and dissimilar pairs of specimens.

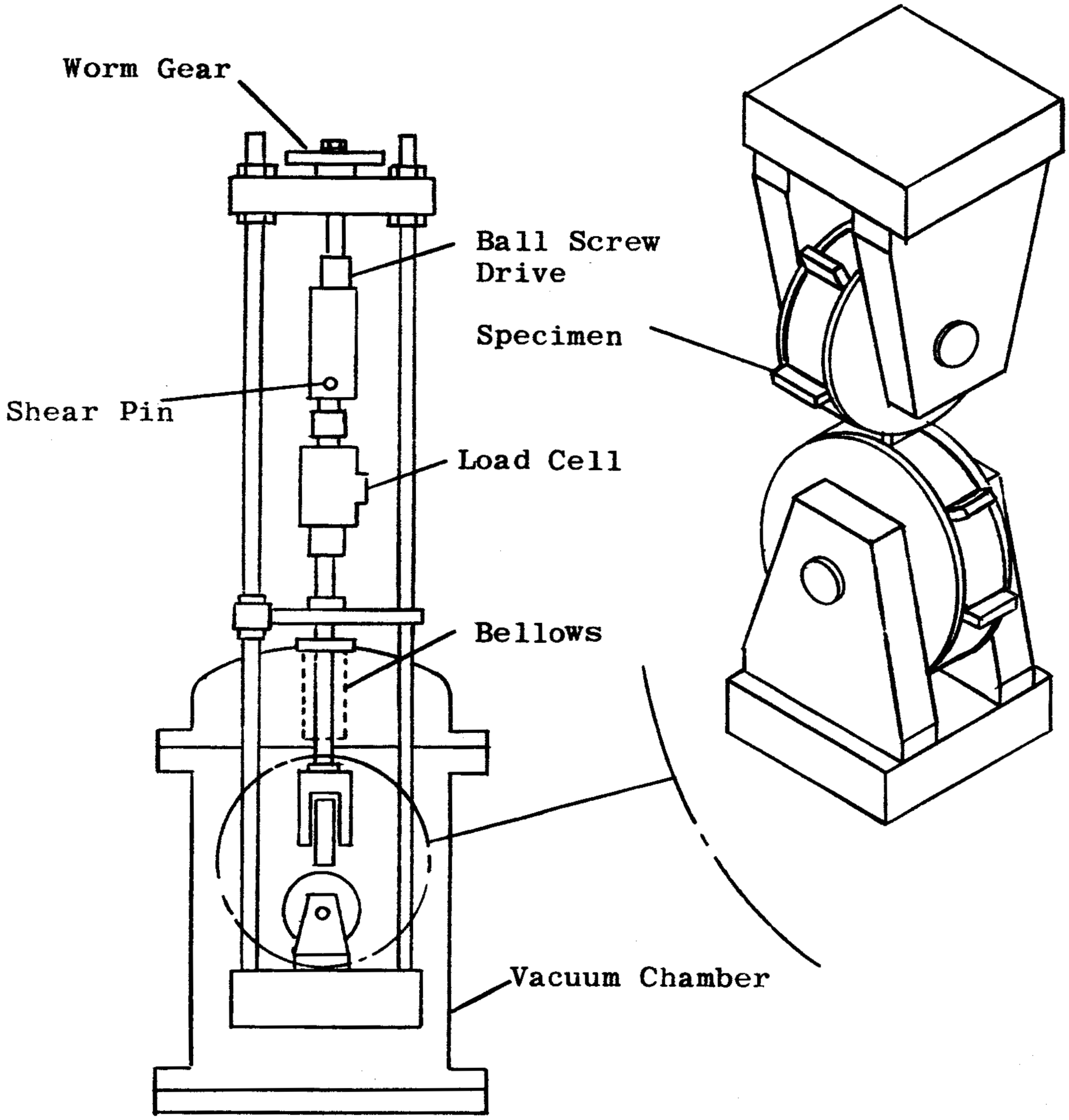
An initial test series consisted of similar material pairs of copper, steel, aluminum and gold, with the major effort on copper. The parameters that were varied included temperature, load, and degree of cleaning. Several tests were performed while varying one parameter at a time. The second test series consisted of dissimilar material pairs.

RESULTS

The effects of various parameters on the adhesion of similar materials were investigated in three test sequences. These included effects of cleaning (via wire brushing techniques), temperature, and loading stress.

Copper specimens were tested extensively at vacuum levels of 10^{-8} to 10^{-9} torr. As shown in Figs. 2, 3, and 4,

FIGURE 1



ADHESION TEST APPARATUS

the adhesion of similar metals was a function of all three parameters, degree of cleaning, temperature and load. The adhesion force tended to increase directly within these parameters. This first series lead to the conclusion that adhesion was stongly affected by plastic deformation and interfacial diffusion. In order to examine the effect of lattice solubility, a second series of dissimilar materials were tested.

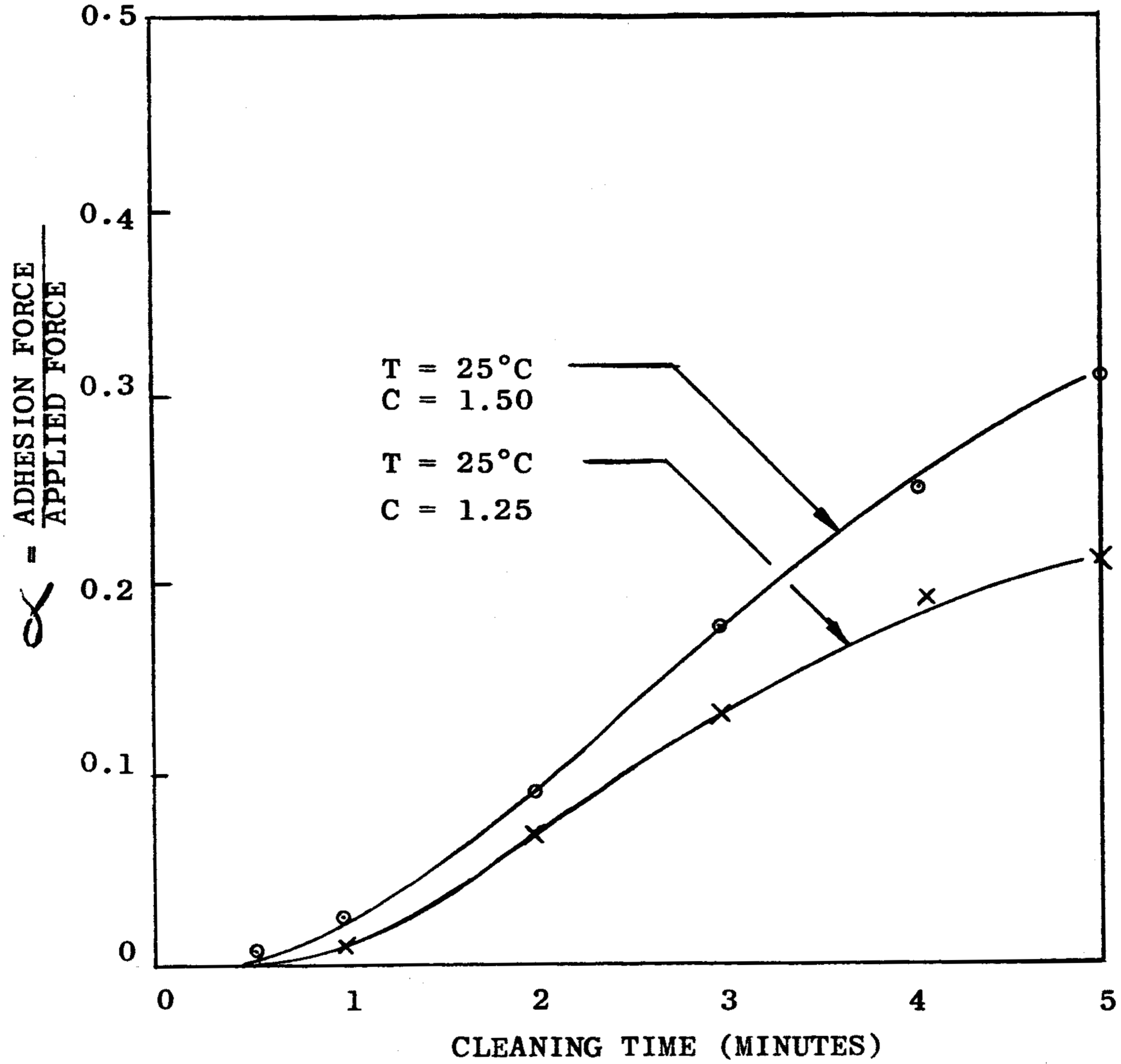
Specimens consisting of two categories of dissimilar material samples; (1) materials that were completely soluble with each other at room temperature and (2) material with less than 0.1% solubility at room temperature were tested. The material pairs are listed in Table I below:

TABLE I

Soluble Pairs	Insoluble Pairs
(100%)	(<0.1%)
Cu - Au	Cu - Ta
Cu - Ni	Ag - Fe
Ag - Au	Ag - Ni
Nb - Ta	Au - Pb

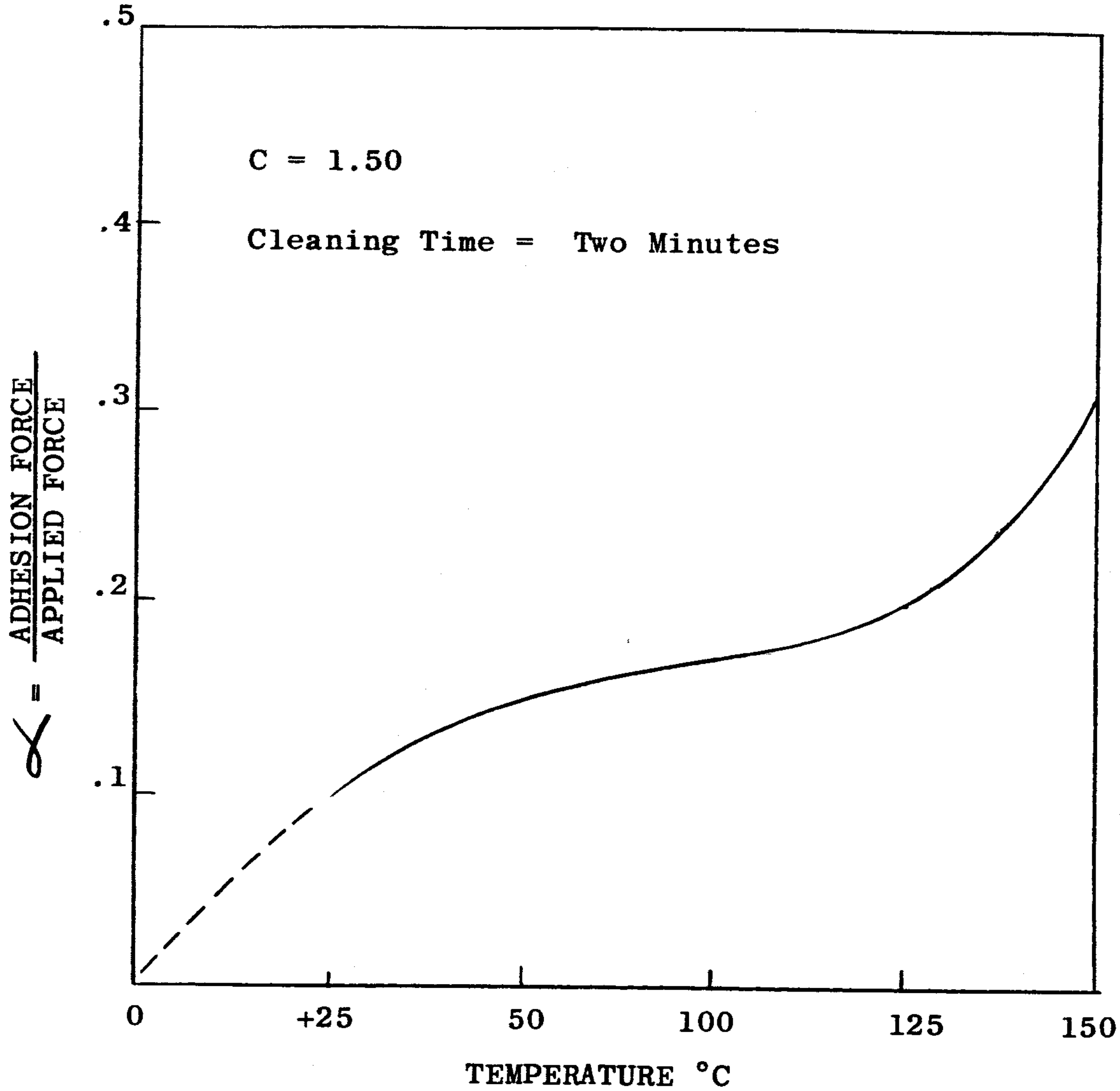
These two solubility levels were selected to examine the importance of the chemical solubility effects as a major mechanism of cold welding. However, experimental results shown in Fig. 5 indicate that adhesion was obtained for both solubility conditions. Again the three reported factors of degree of cleaning, temperature, and loading were the prime test variables. These parameters were all directly related to the amount of cold welding obtained. The insensitivity of adhesion mechanism to bulk lattice solubility properties may

FIGURE 2



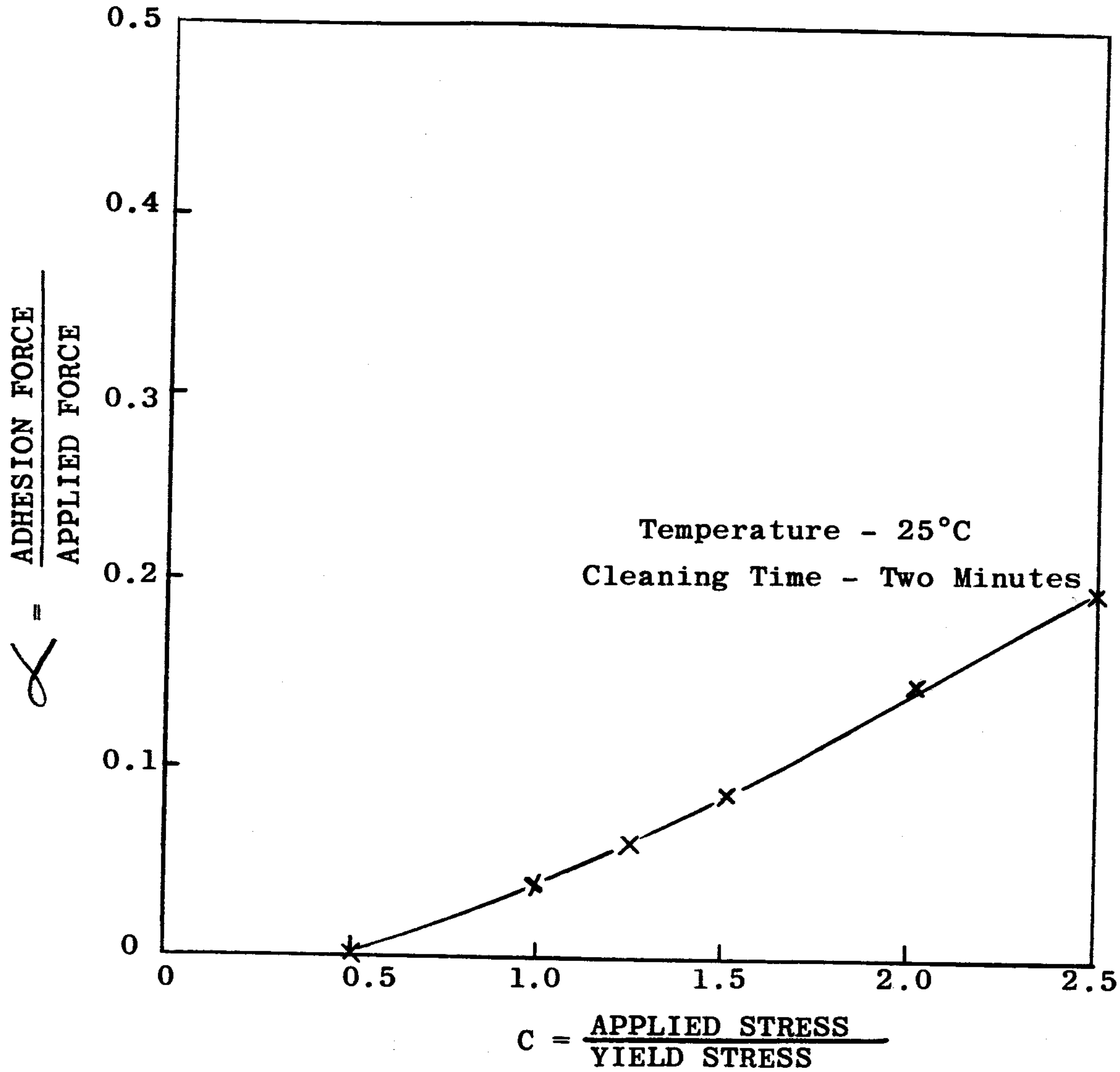
ADHESION AS A FUNCTION OF CLEANING FOR COPPER SPECIMENS USING WIRE BRUSHING TECHNIQUES

FIGURE 3



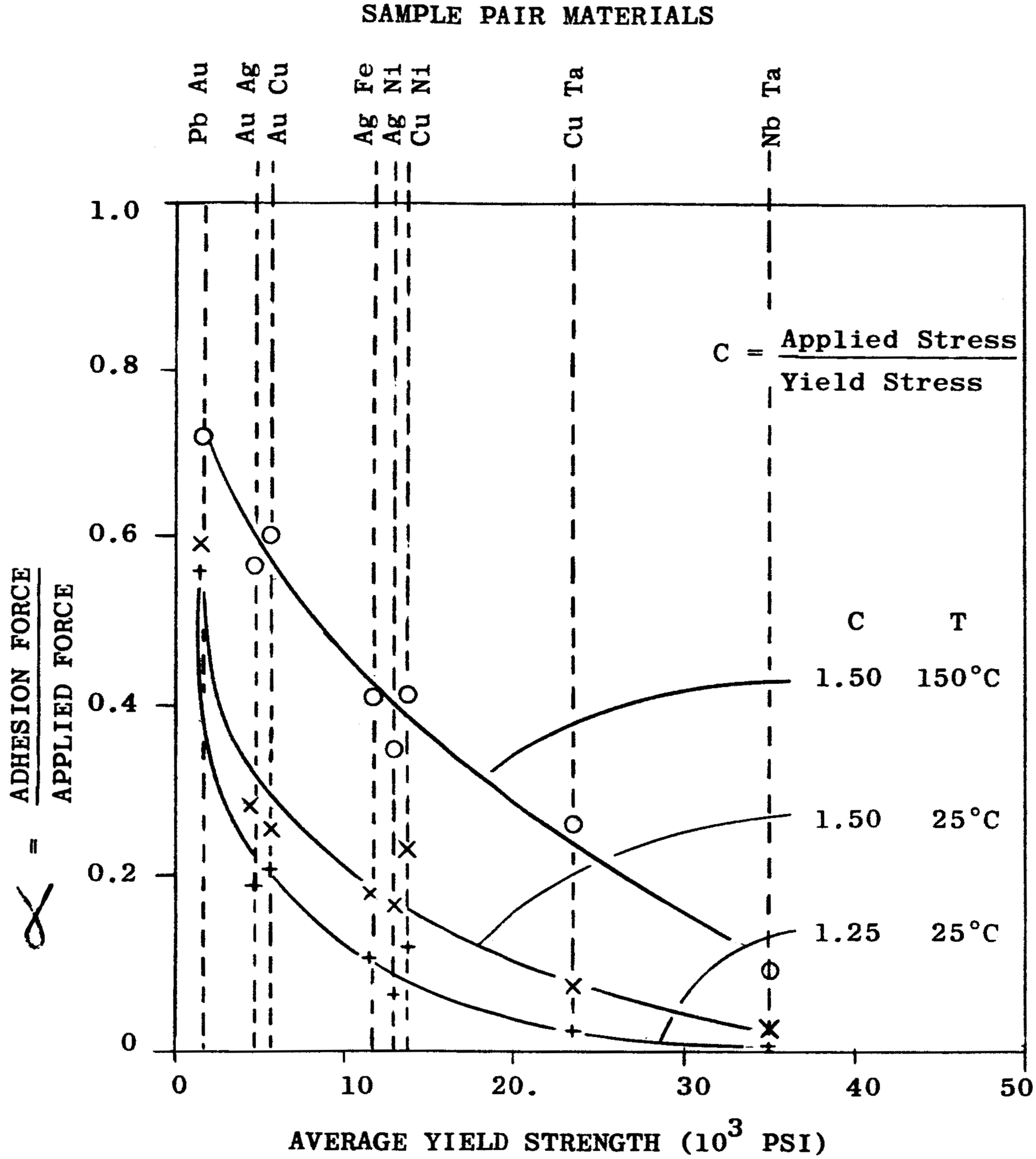
ADHESION AS A FUNCTION OF TEMPERATURE FOR COPPER SPECIMENS USING WIRE BRUSHING TECHNIQUES

FIGURE 4



ADHESION OF COPPER SPECIMENS WITH INCREASE LOADING

FIGURE 5



ADHESION COEFFICIENT AS A FUNCTION IN YIELD STRESS FOR VARIOUS SAMPLE MATERIALS

TABLE II

Other Material Pairs For Which

Adhesion Has Been Reported

Material Pairs	
Al - Al	0.40
2024 - 2024	0.09
6061 - 6061	0.15
Au - Au	0.17
Cu - 1018	0.15
Cu - 4140	0.02
Cu - 440	0.02
Cu - Be Cu	0.20
Cu - Ti	0.08
Cu - Al	0.40
Cu - 6061	0.06
Au - 1018	0.02
6061 - 1018	0.02
6061 - 2024	0.04
6061 - Al	0.01
Au - Al	0.40

be attributed to the relative lattice relaxation at the surface, thus permitting a wider degree of atomic substitution and alloying at the interfacial zone.

A fourth variable was also evident from the results shown in Fig. 5. This was that adhesion or cold welding was related inversely to the hardness (average yield stress) of the material pair.

The present data has dealt with selected materials, however, many materials have been reported to adhere in vacuum. Table II lists other material for which cold welding has been reported along with the maximum adhesion coefficient obtained.

DISCUSSION

From the experimental studies reported above, it is evident that the cold welding phenomenon is of general application for a wide range of engineering metals. Several criteria, however, must be satisfied before successful welding can be achieved:

1. Surface Cleanliness - the strength of the weldment can be directly related to density of metal-to-metal atomic bonds. Hence, the presence of oxide or orgainic films which can bond only very weakly across the interface must be avoided.

2. Plasticity - the ability of the contacting surfaces to plastically flow is necessary to bring the surfaces

into close atomic contact and to relieve elastic restoring stresses generated in localized areas of initial contact. This requirement can explain the relative difficulty in cold welding strong metals with limited ductility such as tungsten or high strength steel compared to softer materials such as aluminum or copper.

3. Temperature - increasing the contact temperature tends to lower the yield stress and increase ductility. An increase in temperature to values above 1/2 T_{mp} (melting point) also leads to extensive diffusion bonding across the interface.

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